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Personal data logging monitors provide real-time measurement of pollutants and have the ability to store data over an extended period of time. As such, they can be used to provide warning to workers that high concentrations are present, as well as allowing the assessment of long-term worker exposure. The performance characteristics of these monitors are fundamental to the determination of the accuracy of the warning and exposure measurement data. In this study, the performance characteristics of one type of personal carbon monoxide (CO) data logger (Draeger 190) were evaluated.

The monitor displayed linear response over the concentration range 0 to 950 ppm. The 12-hour zero drift for the monitor was less than 1 ppm, and the 12-hour span drift was less than 2 percent at 100 ppm. The monitor showed less than 3 percent variation in response for CO concentrations of 20 ppm to 100 ppm when exposed to CO concentrations in a repeated cycle. The long-term response stability showed a coefficient of variation of 9 percent at 57 ppm for response data taken over a 3-month period, where the monitor was calibrated at a 30-day interval. The monitor was found to reach 90 percent of final response within 20 seconds. Changes in humidity did not affect monitor response, while response did increase with temperature over the range of 0°C to 40°C. The temperature response varied between monitors and for different concentration ranges. Some interferences (nitric oxide, nitrogen dioxide, hydrogen sulfide, and sulfur dioxide) were completely removed by the CO-specific filters on the monitors, while other interferences (acetylene, ethylene, and hydrogen) were not. Also, the response to acetylene was affected by the condition of the CO-specific filter. The monitor also responded to hair spray when it was sprayed near the monitor. The hair spray produced a full scale response if it was sprayed directly on the monitor. Smith, J. P.; Shulman, S. A.: Evaluation of a Personal Data Logging Monitor for Carbon Monoxide. Appl. Occup. Environ. Hyg. 9(6):418-427; 1994.

Introduction

Carbon monoxide (CO) is a colorless and odorless gas that decreases the ability of the blood to carry oxygen to the tissues. Exposure to high concentrations can be rapidly fatal without producing clear warning symptoms. Exposure to CO is responsible for a significant number of workplace and residential deaths. Exposure to lesser concentrations can aggravate cardiovascular diseases.[1] The National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) is a 35-ppm time-weighted average (TWA) with a 200-ppm ceiling.[2]

The ideal monitor for CO should be able to provide 1) an immediate warning of high CO concentrations through audio or visual alarms and 2) an estimate of worker exposure for short-term ceiling levels and long-term (8 to 10 hours) TWA levels. Detector tubes for long-term measurements can provide an integrated time estimate of long-term worker exposure, but cannot provide warnings of transient high concentrations. Detector tubes for short-term measurements can give warning of high concentrations, but are not practical for short-term or long-term exposure estimates.[3]

Personal direct reading monitors for CO have been commercially available for some time. Most of these monitors use an electrochemical detection principle for the measurement of CO.[4] The original use for these monitors was limited to providing alarms when high CO concentrations were present. The recent development of personal monitors with data logging capability has increased their usefulness since they now can provide personal exposure estimates and information on the temporal nature of the exposure. Also, these monitors can provide an alarm function to warn of high CO levels.

The performance of the same personal CO monitor that was evaluated in this study was examined briefly in previous studies, but no extensive study of its performance was conducted.[5,6]

In this study, operating characteristics of a personal CO data logger were examined. The parameters related to monitor performance that were studied include: response linearity, response stability, time response, and response under varying conditions of temperature, humidity, and interferences.

Experimental

CO Monitors

The monitor evaluated in this study was the Draeger 190 data logger CO monitor (National Draeger, Pittsburgh, Pennsylvania). This monitor was chosen for study because it has been used by the Occupational Safety and Health Administration (OSHA) to determine workplace compliance with OSHA standards and has been used by NIOSH researchers in a number of field studies. The monitor is 124 mm × 60 mm × 25 mm and weighs approximately 200 g. It has a digital LCD display which cycled between the present concentration, the TWA concentration, and the peak concentration for the monitor's present measurement cycle, displaying the concentration to the nearest ppm. Data were stored in the monitor to the nearest ppm for a measurement cycle up to 12 hours. The data were stored as average concentrations for each 1-minute time period. The monitor must be reset manually using a key (an electrical plug that fits onto an electrical socket on the monitor) to start a measurement and data storage cycle. Use of the key, which is external to the monitor, instead of a button on the monitor lessens the possibility of tampering with the monitor once data acquisition has been started. After a measurement cycle was completed, the stored data were transferred to an IBM compatible computer using a cable with an electrical plug (Converter Box, National Draeger) that fits onto the electrical socket on the monitor, and software (Enhanced Graphics Software, Version 2.0, National Draeger) that was purchased from the manufacturer.

Six copies of the monitor were equipped with new sensors for this study. The sensors were small modules which measured CO using an electrochemical principle of operation and sampled the air via diffusion. These monitors were designated with a letter (A,B,C,D,E,F) for convenience of monitor identification. The monitors used 9-volt batteries that must be replaced periodically.

The monitor employed either a nonspecific filter or a CO-specific filter which fit over the sensor. The CO-specific filters were able to remove some interferences to which the monitors responded. The CO-specific filters were used when interferences were present, while the nonspecific filters were used when no interferences were present. The CO-specific filters were used for this study except where mentioned. The nonspecific filters were used to measure the monitor response to interferences without the specific filters. The monitors had a range of 0 to 999 ppm and a single level audio and visual adjustable alarm.

The monitor was calibrated at an interval of 30 days. This interval was chosen to see how much the monitor response changed over this time period. These calibration procedures involved zeroing the monitors with pure air and then adjusting the monitors' output with the monitors exposed to calibrated CO concentrations in air using a regulator that provided a constant flow of 200 ml/min. A calibration adaptor (a hose with a cap that fitted over the filter and sensor of the monitor) was used for calibration. The monitors were calibrated with 250-ppm CO mixtures in air obtained from the monitor manufacturer.

Gas Generation Systems and Exposure Chamber

To study monitor linearity, reproducibility, and monitor response under various conditions of temperature and humidity, a computer-controlled gas generation system was constructed. This generation system (Figure 1) was used to produce varying concentrations of CO using a calibrated mixture of CO in air (nominal concentration of 5008-ppm CO in air) (Scott Specialty Gases, Plumsteadville, Pennsylvania). The generation system used mass flow controllers to control the flows of the pure air and the calibrated CO mixture in air. The mass flow controllers (Tylan model 260, Tylan, Torrance, California) were controlled by a computer using a Taurus interface (Taurus One, Taurus Computer Products, Amherst, New Hampshire) which produced analog outputs using digital-to-analog converters that were used to control the outputs from the flow controllers. The computer transferred commands to the Taurus interface using a serial interface to control the gas flows. The humidity was controlled by passing an appropriate portion of the pure air over a heated water reservoir. The CO monitors themselves were enclosed in a small instrument exposure chamber into which the mixture containing various CO concentrations was introduced. Six monitors were put into the chamber at one time and the chamber positions were numbered 0 to 5.

When experiments were performed at a high or low temperature, the entire generation system was enclosed in a

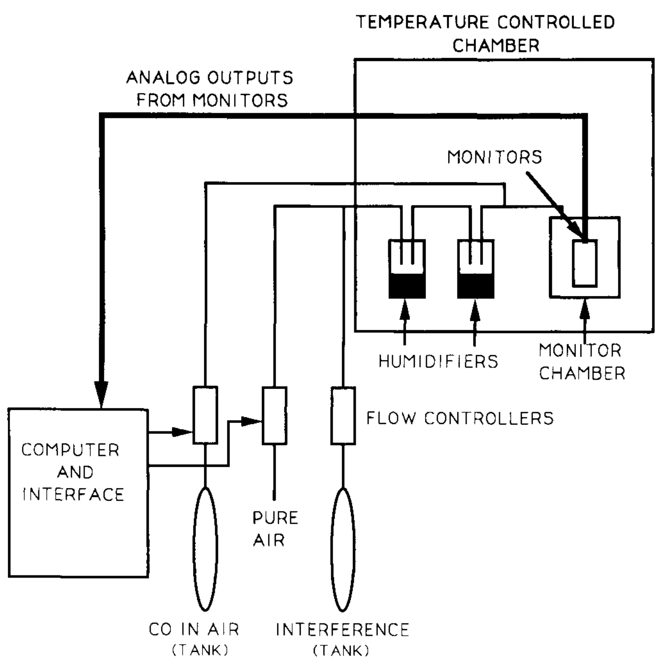

FIGURE 1. Computer controlled CO gas generation system.

larger temperature-controlled chamber that could be heated to 40°C or cooled to 0°C. The air entering the instrument exposure chamber passed through a temperature equilibration coil to allow it to come to the proper temperature before introduction into the instrument exposure chamber. The gas concentrations produced by the gas generation system were verified by measurements using a Fourier transform infrared spectrometer (Nicolet Model 60SX, Nicolet Analytical Instruments, Madison, Wisconsin) equipped with a 10-m gas cell. The concentration calculated from dilution of the CO calibrated mixture by the gas generation system was used in developing plots and response functions produced in this study.

Computer programs were written in BASIC[7] to control the CO concentrations to which the monitors were exposed. These programs provided outputs to the Taurus interface to control the CO mixture and pure air flows. To conduct an experiment, a computer file containing the concentrations and associated time intervals was entered into the computer. During each experiment, the analog outputs from the monitors were transferred to the computer and stored. After each experiment was completed, the internally stored monitor data were transferred to the computer using hardware and software obtained from the monitor manufacturer. These data and the data from each monitor's analog port that had been digitized and stored in the computer were averaged for each time interval. Data collected during equilibration of the CO concentration in the instrument exposure chamber were not used. The average monitor response was determined for each generated concentration.

Response Linearity and Response Stability

Experiments were conducted to assess the linearity of the monitor response and the short- and long-term stability of monitor response. Most of the experiments were conducted at approximately 50 percent relative humidity. These experiments were divided into sets which consisted of placing each monitor at one of the six positions in the chamber, and then challenging the monitors at eight different concentrations of CO varying from 0 to 250 ppm CO. These sets were collected over a period of 3 months with each monitor randomly placed at each position. A limited number of runs were conducted at 250 to 950 ppm CO to assess monitor response in the higher concentration range.

Response linearity was determined by fitting polynomials to the monitors' response as a function of concentration.

The stability of response was studied in several different ways. As a measure of short-term stability, the 12-hour zero drift, 12-hour span drift, and the variation in response when the monitors were exposed to varying concentrations of CO in a repeated cycle, were studied. The 12-hour zero and span drift were studied by exposing the monitors to zero air or to a concentration of about 102 ppm CO and measuring the monitor response stability with time. The monitors were not zeroed or spanned before these experiments since the monitors were zeroed and spanned at intervals recommended by the manufacturer. In the other experiment, the monitors were exposed to CO concentrations varying from 10 to 102 ppm in a repeated cycle. This cycle was repeated four times and the variation of monitor response from cycle to cycle was evaluated. These experiments give an estimate of how much the monitor response changed during a single measurement period.

For a measure of long-term stability, the monitor response to CO concentrations ranging from 0 to 250 ppm was measured over a 3-month period, during which the monitors were calibrated at a 30-day interval. The variation in the monitor response was then calculated. These are the same data that were used to assess the linearity of monitor response. This gave an estimate of how much the monitor response varied over a time interval between calibrations.

Response Time

Response time is the time that the monitor response takes to reach some fraction of the final response. The response time was measured by exposing the monitors to a 250-ppm CO calibration mixture or a 25-ppm CO calibration mixture with the calibration adaptor. This allowed the rapid change of the exposure concentration. The estimated time to reach the final concentration was about 3 seconds based on the volume of the calibration adaptor and the flow rate from the regulator. The response cycle was started by turning on the flow of gas to the calibration adaptor at the regulator, and measuring the output from the monitors using the analog output. The fall time was determined by removing the calibration adaptor from the monitor and measuring the time the monitor took to return to various fractions of zero response.

Response under Varying Humidity and Temperature Conditions

The effects of varying humidity and temperature on monitor response were studied in a factorial design experiment. The temperature range studied was 0°C to 40°C and the humidity range was 0 to 100 percent. The extremes in temperature (0°C and 40°C) and humidity (0% and 100%) and a midpoint (25°C, 50% relative humidity) were studied. The results of these conditions were evaluated in the 0 to 250 ppm range.

The order in which the experiments were performed reflected the difficulty of changing temperature and humidity. It was easier to vary the CO concentration while keeping temperature and humidity fixed. Thus, the design used was not a complete randomization. Two replicates of the design were run. At each temperature–humidity setting, a different randomized placement of monitors in the chamber was used. The order of the CO concentrations was randomized from one temperature–humidity condition to the next.

Effect of Interferences

Interferences were chosen on the basis of which compounds might be present along with CO in workplaces such as steel manufacturing or those using welding [hydrogen sulfide (H_2S), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), ethylene, acetylene, and hydrogen]. Various interferences were obtained as mixtures of the interferant gas of interest in air or N_2 (Scott Specialty Gases). These were used to expose the monitors to the interferences using the calibration adaptor. Response to interferences was studied in a number of different ways depending on the particular interference being studied. The reactive interferences [hydrogen sulfide (H_2S), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2)] were obtained as gaseous mixtures. The monitor response to these interferences was measured by exposing the monitors to the gaseous mixtures using the calibration adaptor. Less reactive interferences (ethylene, acetylene, and hydrogen) were obtained as mixtures at higher concentration and had to be diluted before exposing the monitors to these interferences.

A number of experiments were conducted with acetylene to examine the effect of the CO-specific filter condition on the monitor response to acetylene. The CO-specific filters contain an unspecified chemical reagent that removes the interferant gas but not CO. Therefore, as the age of the specific filter increases, the reagent could be expended and the filter could become less effective in removing the interference. In the first of these experiments, specific filters of varying age were chosen. The response of three of the monitors to 250 ppm CO (alone) and 82 ppm acetylene (alone) was measured using each of these specific filters and one of the nonspecific filters. In this experiment the available set of filters was divided into several groups. The particular groups were as follows:

1. nonspecific: one filter in this group;
2. old specific filters (more than 1 year old): six filters in this group;
3. newer specific filter (2.5 months old): three filters in this group; and
4. newest specific filter (1 week old): one filter in this group.

The purpose of the experiment was to study the biases in the monitor response to acetylene associated with use of different filters. All runs were made with each filter on one monitor before proceeding to the next monitor. By design, the measurements with one of the monitors was replicated. Only one concentration of CO and acetylene was used in this experiment and both gases were run with each filter before proceeding to the next filter. Another experiment was conducted in which all six monitors were supplied with new specific filters. This experiment exposed the monitors to CO and acetylene in a mixture to see if the presence of acetylene affected the monitors' response to CO.

The monitor response to CO concentrations between 10 and 50 ppm, with and without the presence of 27 ppm acetylene, was measured over a 1-week period to study how the exposure of the specific filter to acetylene affected the monitor response to acetylene and CO. It was necessary to expose the specific filters to 1500 ppm acetylene for 1 hour between certain of the runs of the experiment to demonstrate a change in response with time.

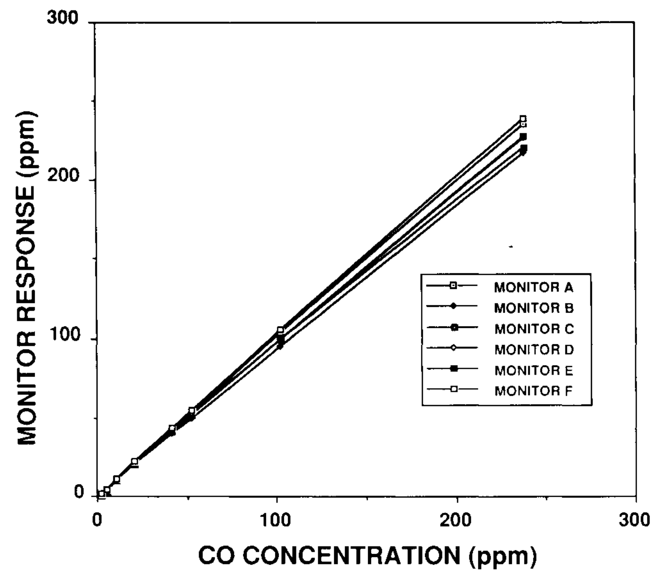

FIGURE 2. Monitor response as a function of concentration for 0 to 250 ppm CO.

Since the monitors are made to be worn on a person, they could potentially be exposed to personal care products. Therefore, the response of the monitors to hair spray was determined. For hair spray no quantitative evaluation of the monitors' response was obtained. In attempting to determine the source of the response to hair spray, two of the monitors were exposed to ammonia over a concentrated solution of ammonium hydroxide but no quantitative measure of response was obtained.

Results and Discussion

Response Linearity

Most of the experiments examining response linearity were conducted between 0 to 250 ppm CO since this concentration range covers existing exposure limits, such as the OSHA permissible exposure limit (PEL) and NIOSH REL. Figure 2 shows the monitor response over this concentration range. As expected, the monitor response was linear over this concentration range. Polynomials were developed to describe the monitor response, and the linear component accounts for over 97 percent of the response with a small deviation explained by the quadratic component. The combined linear and quadratic components account for over 99 percent of the variation in the response. The monitors displayed linear response in the 250 to 950 ppm concentration range, with the slopes of the curves varying from 0.95 to 1.05.

Response Stability

As explained earlier, the short-term response stability was studied by examining the 12-hour zero drift, 12-hour

TABLE I. Results of Short-Term Stability Tests

Monitor	Average[A]	12-Hour Zero Drift (ppm) Stand. Dev.[B]	Start[C]	End[D]	Change[E]
A	0.02	0.13	0.18	0.0	0.18
B	0.18	0.39	0.73	0.0	0.73
C	0.0	0.0	0.0	0.0	0.0
D	0.0	0.0	0.0	0.0	0.0
E	−2.0	0.06	−2.0	−2.0	−0.05
F	0.0	0.0	0.0	0.0	0.0

Monitor	Average[A]	12-Hour Span Drift (102 ppm) Stand. Dev.[B]	Start[C]	End[D]	%Change[F]
A	100.5	0.5	100.0	100.1	0.14
B	101.8	0.81	100.1	102.0	1.9
C	91.9	0.25	92.0	91.6	0.5
D	97.8	0.66	96.8	98.0	1.2
E	106.4	0.49	106.0	106.0	0.0
F	117.2	0.45	116.8	117.0	0.18

Target Concentration (ppm)	Monitor Response to Concentration in Repeated Cycle A	B	C	D	E	F
10.5	11.0 ± 0*	11.0 ± 7.2	9.9 ± 2.0	9.9 ± 6.1	8.6 ± 12.8	12.8 ± 4.7
21	21.7 ± 2.3	22.0 ± 3.2	19.5 ± 2.6	20.0 ± 0	19.8 ± 1.5	24.6 ± 0.8
41.9	42.5 ± 1.4	42.8 ± 2.1	39.7 ± 1.8	40.9 ± 0.2	43.2 ± 0.9	49.0 ± 0.6
52.8	53.2 ± 0.8	53.2 ± 1.3	50.0 ± 1.6	51.4 ± 0.9	55.1 ± 0.7	61.7 ± 0.3
102	100.1 ± 0.3	99.3 ± 0.6	92.5 ± 1.1	96.0 ± 0.2	106.2 ± 0.6	116.2 ± 0.3

*Mean measured concentration ±%CV.
[A]Average measured concentration for exposure period.
[B]Standard deviation of measurements during exposure period.
[C]Average measured concentration during first hour of exposure period.
[D]Average measured concentration during last hour of exposure period.
[E]Start-End.
[F]((Start-End)/Average) × 100.

span drift and the reproducibility of response, when the monitors were exposed to varying CO concentrations in a repeated cycle. The results of the zero drift experiment are presented in Table I. The values shown for the beginning and end of the exposure period are average concentrations measured by the monitors over the first and twelfth hour of the exposure to zero air. Three of the six monitors showed no zero drift during the time period while the other three had zero drift less than 0.8 ppm. Therefore, zero drift should contribute less than 1 ppm to the measurement error over 12 hours.

The data on span drift for the monitors are shown in Table I. The monitors were exposed to a concentration of CO calculated to be 102 ppm for 12 hours. The values shown for the beginning and end of the exposure period are average concentrations measured by the monitors over the first and twelfth hour of the exposure. The span drift ranged from 0 to 1.9 percent of the average measured concentration. The standard deviation of the average measured concentration varied from 0.27 to 0.80 percent of the average concentration. The results of the experiment wherein the monitors were exposed to varying CO concentrations in a repeated cycle are also shown in Table I. Over a 6-hour period, the monitors were exposed four times for 15 to 20 minutes. The highest variation in measurement was at the lowest concentration where the variation was as large as 12.7 percent for Monitor E at 10.5 ppm CO. For all other concentrations, the standard deviation was less than about 3 percent of the mean concentration.

As a measure of long-term stability, the monitor response for the 0 to 250 ppm concentration range was measured over a time period of 3 months. To estimate the variability over monitors and time, an analysis of variance was conducted, in which different variance components were estimated. These estimates indicated that the total coefficient of variation (CV) was about 9.3 percent at the overall mean concentration of 57.2 ppm. This total variability includes all components except for variability associated with the use of eight different concentrations of CO. More than 50 percent of the total relative standard deviation was due to shifts in the response of the monitors over time. The remainder of the variability includes variability between monitors, variability of monitors over time, variability of monitors with concentration, and within monitor variability.

Response Time and Fall Time

Figure 3 shows the monitor response when exposed to 250 ppm CO or 25 ppm CO using the calibration adaptor. The response of all the monitors was reproducible with a

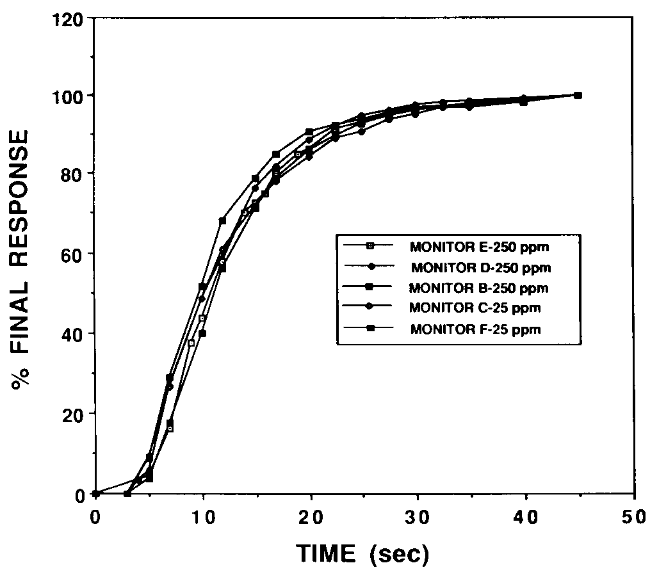

FIGURE 3. Monitor response as a function of time after monitors were exposed to 25 ppm or 250 ppm CO.

lag time of less than 5 seconds compared with an estimated 3 seconds to reach the final concentration in the calibration adaptor. The time to reach various response levels was also reproducible: 50 percent response was reached in 10 seconds, 70 percent response was reached in 14 seconds, and 90 percent response was reached within 20 seconds. The response time did not appear to be concentration-dependent since response to 25 ppm and 250 ppm were the same.

Figure 4 shows the monitor response for monitors that were exposed to 250 ppm or 25 ppm and then to clean air. There seemed to be a variable lag time in monitor response which may have been due to a variable length of time in removing the calibration adaptor from the monitor. The time to reach zero was reproducible. As in the case of response time, the monitors reached 50 percent of final response in 10 seconds, 70 percent final response in 15 seconds, and 90 percent final response within about 20 seconds.

Effects of Temperature and Humidity

As described in the Experimental section, a factorial design experiment was conducted to measure the effects of temperature and humidity. The response was measured over the same concentration range (0 to 250 ppm) that was used to study linearity. Three temperatures (0°C, 25°C, and 40°C) were studied and a humidity range of 0 to 100 percent relative humidity was used. Analysis of variance methods were used to perform significance tests and to estimate variance components.

It was found that none of the humidity effects—whether main effects or interactions—was statistically significant. The main finding was that as temperature increases, the monitor response increases. At 0°C, the average response is about 55.8 ppm; at 25°C, 63.8 ppm; and at 40°C, 69.0 ppm (Table II). However, the temperature effect varies by CO concentration. At the higher concentrations, the 25°C and 40°C results appear to be similar, while the 0°C results are somewhat lower (Figure 5). At the lowest concentration, there was a fourfold difference in response from lowest to highest temperature. This probably was due to the increase in monitor zero with temperature. A small increase in zero will affect the response to low concentrations more than the response to the higher concentrations. Thus, the temperature × CO concentration interaction seemed to be due to the fact that the 25°C readings changed in their relation to the 0°C and 40°C readings, as the CO concentration increased.

The individual monitors varied in their response to temperature and concentration (Table II). The most temperature-sensitive monitor had an average response of 46.2 ppm at 0°C and 67.7 ppm at 40°C, while the least temperature-sensitive monitor had an average response of 55.3 ppm at 0°C and 63.3 ppm at 40°C. The monitors also differed in their response to varying concentration. For instance, monitor D had the lowest mean response (3.5 ppm) at 2.4 ppm CO and the second highest mean response (246.6 ppm) at 238 ppm CO; while monitor B had the highest mean response (6.2 ppm) at 2.4 ppm CO concentration and the lowest mean response (199.0 ppm) at 238 ppm CO. Also, monitors varied by the combination of both concentration and temperature.

The manufacturer's data indicate that response goes up with temperature from 0°C to 10°C, is relatively constant from 10°C to 30°C, and then goes down with temperature from 30°C to 40°C. In this study, however, the response increased with temperature over the range of 0 to 40°C which is in agreement with another study.[3]

Response to Interferences

Interferences can provide two types of effects on response. Positive interference is an effect which increases monitor response. Negative interferences is an effect which

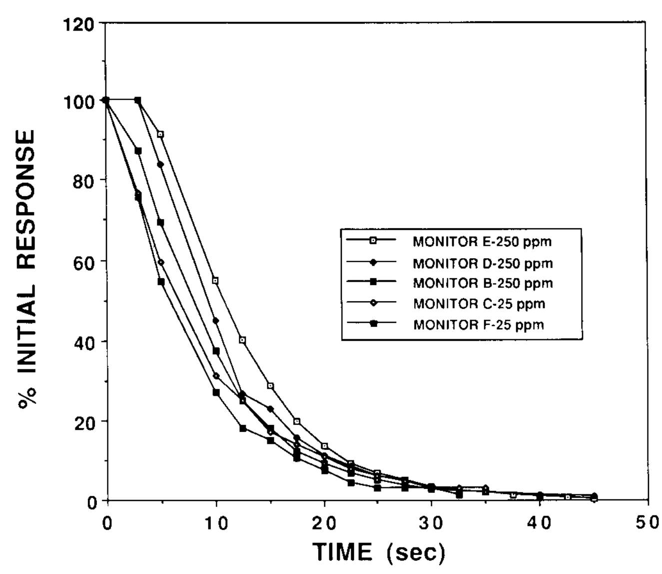

FIGURE 4. Monitor response as a function of time when monitors were exposed to 25 ppm or 250 ppm CO and then exposed to clean air.

TABLE IIA. Average Response Over Eight CO Concentrations at Three Temperatures for the Six Monitors (ppm)

	Monitor						
Temp.	A	B	C	D	E	F	Avg.
40°C	63.3	63.0	67.7	82.8	72.4	70.9	69.0
25°C	60.9	57.2	60.6	67.7	67.9	69.2	63.8
0°C	55.3	52.5	46.2	66.0	54.1	62.1	55.8

TABLE IIB. Average Response Over Three Temperatures for Six Monitors at Eight CO Concentrations

	CO Conc. (ppm)							
Monitor	2.4	5.1	10.5	21.0	41.9	52.9	102	238
A	4.8*	7.7	13.4	24.9	47.3	59.2	109.3	213.3
B	6.2	8.4	13.3	24.3	45.8	58.1	104.8	199.0
C	5.0	7.4	13.5	24.4	46.4	57.2	106.2	208.1
D	3.5	6.2	13.8	26.3	51.9	65.1	121.2	246.6
E	4.1	6.7	12.6	24.8	45.3	60.4	112.4	228.8
F	5.6	8.5	15.1	28.2	54.0	67.0	124.7	247.6

*Response of the monitor averaged over three temperatures at the indicated CO concentration.

decreases monitor response such that the monitors will have a response less than the amount of CO present. Of the gases studied (H_2S, NO, NO_2, ethylene, acetylene, and hydrogen), all provided a positive interference.

The interferences studied could be divided into three different classes. The first type of interferences were relatively reactive gases (H_2S, NO, NO_2, SO_2) and were removed efficiently by the CO-specific filters provided with the monitors. The second type of interferences were the less reactive gases (ethylene, acetylene, and hydrogen) that were removed less efficiently by the specific filters. Some of these interferences were removed to a variable extent depending upon the condition of the specific filters. The third type of interference was produced by the spraying of hair spray near or onto the monitors.

Table III shows the monitor response to several reactive gaseous interferences in the absence of CO. When the nonspecific filter is used, the monitors responded more to two of these interferences (H_2S and NO) than to an equivalent CO concentration. For the rest of the interferences, the monitors responded less to the interferences than to an equivalent CO concentration. However, when the CO-specific filter was used, the response to each of these interferences was completely removed. These filters were effective in removing these interferences when the filters were new.

Filter age proved to be an important factor in determining the effectiveness of the specific filters in reducing response to less reactive interferences such as acetylene, but filter age was not investigated for more reactive interferences.

Table III shows the monitor response to less reactive interferences such as hydrogen, ethylene, and acetylene. When the nonspecific filters were used, the monitors responded more to ethylene and acetylene than an equivalent CO concentration. The specific filter removed part, but not all, of the response to these interferences. The monitors responded much less to hydrogen than an equivalent amount of CO, and the specific filter did not remove a significant part of the interference.

As mentioned in the Experimental section, several additional experiments were conducted to examine the effect of specific filter age on the monitor response to acetylene. In the first of these experiments, the monitor response to 82 ppm acetylene alone and 250 ppm CO alone was studied with CO-specific filters of varying ages and a nonspecific filter. Table IV summarizes the results of this experiment. For acetylene at 82 ppm, at the 5 percent significance level, the nonspecific, and old CO-specific filters yielded responses that are higher than the other specific filters. The mean response over all measurements for acetylene was 206.5 ppm. The nonspecific filter yielded determinations that were 210.5 ppm higher than the newest CO-specific filter. The oldest CO-specific filters yielded responses that are 163.3 ppm higher than the newest CO-specific filter. These differences can be compared with the standard deviation of a measurement which was 38 ppm or 18.4 percent of the mean response of 206.5 ppm. Note that even the newest CO-specific filter did not remove all of the acetylene response.

The response to 250 ppm CO was similar for all the groups of filters. The newest and newer CO-specific filters were statistically indistinguishable. The nonspecific filters gave CO responses that were about 29 ppm higher than either the newer or newest CO-specific filters. The oldest CO-specific filters gave determinations that are about 10 ppm lower than the newer or newest CO-specific filters. These differences can be compared to the standard deviation of the measurement which is 9.2 ppm and amounts to 3.7 percent of the mean response. Although the above dif-

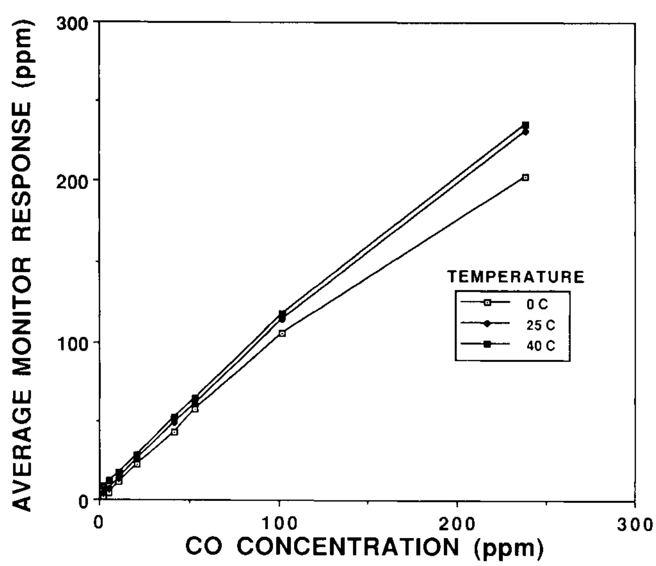

FIGURE 5. Average monitor response as a function of concentration at three temperatures.

TABLE III. CO Monitor Response to Interferences in the Absence of CO

Interference	Relative Reactivity	Response (ppm CO)	
		Nonspecific Filter	Specific Filter
H_2S, 99 ppm	Hi	400 ± 42	0 ± 1
SO_2, 25 ppm	Hi	13 ± 4	0 ± 1
NO, 19 ppm	Hi	32 ± 5	0 ± 1
NO_2, 23 ppm	Hi	2.5 ± 0.5	0 ± 1
Ethylene, 133 ppm	Lo	237 ± 46	32 ± 27
Hydrogen, 1000 ppm	Lo	80 ± 26	75 ± 22
Acetylene, 82 ppm	Lo	265 ± 18	140 ± 18

ferences are statistically significant, they are much smaller than the corresponding differences for the acetylene measurements.

As described in the Experimental section, another experiment was performed in which the monitor response to 10 to 50 ppm CO was measured with and without the presence of 27 ppm acetylene. The results of a typical experiment with one monitor (monitor A) are shown in Figure 6 and results for all the monitors are presented in Table V. In Figure 6, CO + ACET refers to the monitor's response to varying concentrations of CO in the presence of 27 ppm acetylene, while CO alone refers to the monitor's response to CO alone. Data from two different runs performed on two different days are presented. The monitors were exposed to 1500 ppm of acetylene for 1 hour between the two runs. The monitor response is described as a linear function of CO concentration with a slope and intercept. When the monitors were exposed to CO alone, the intercept was near zero as expected. The intercept was the same before and after the monitor was exposed to 1500 ppm of acetylene. When the monitors were exposed to CO in the presence of acetylene, the intercept increased to a value that depended on the condition of the CO-specific filter. However, the slope was about the same as when the monitor was exposed to CO alone, indicating that the response to CO was not affected by the acetylene present. The intercept became larger after the monitors were exposed to 1500 ppm acetylene for 1 hour, indicating that aging of the CO-specific filters could affect the response of the monitors to acetylene, but this aging had little effect on the response to CO as indicated by the relatively constant slope of the response curves. The intercept of the response curve was also variable (varied from 64 to 38 for the different monitors after exposure to 1500 ppm acetylene) (Table V), indicating that aging of the selective filter can cause variation in the monitor response to acetylene. This occurred even though all monitors were exposed to the same concentration of acetylene (1500 ppm).

Additional Interference Tests

The third type of interference was produced by spraying hair spray on or near the monitors. It was difficult to give a quantitative value to this interference since the monitor response varied depending on how the product was sprayed. Hair spray (Gillette Dry Look) was studied most extensively. The hair spray could give a response greater than 999 ppm CO (the maximum monitor reading) if the hair spray was sprayed directly on the monitor. It was demonstrated that the volatile components of the hair spray caused the response. A quantity of the hair spray was pipetted into a bag and the monitor was exposed to the volatilized components of the hair spray. The monitors responded to these volatilized components. The recovery of the monitor response to hair spray was also slow. The monitors took 6 minutes to reach 90 percent of final response after exposure to smaller amounts of hair spray (producing responses of 15 ppm or less) and could take several hours to return to zero after exposure to large concentrations of hair spray.

Exposure to high concentrations of ammonia was found to damage the sensor in the monitors. When two monitors were exposed to the vapors over a concentrated solution of ammonium hydroxide for about 1 minute, the monitors showed a response of about 40 ppm to the ammonia. The monitor response to CO was reduced and the sensors had to be replaced.

Monitor Malfunctions

When the monitors were first obtained, the sensors were replaced to begin the study with new sensors. The sensors lasted the period of the study (11 months) except for those that had to be replaced after exposure to ammonia. The sensor on one monitor had begun to show increased long-term span drift and yielded lower values than the other sensors at the end of the time period. The monitors were operated continuously (although only intermittently exposed to CO concentrations) during this time period and were taken on two field trips. Each field trip lasted 1 week where the monitors were used to measure the exposure of toll booth workers to CO. The only maintenance was the periodic replacement of the batteries.

There were several types of malfunctions identified. Occasionally, after the data were read using the software provided by the manufacturer, the monitors could not be reset to start a new data acquisition period using the key that is provided for this purpose. In this case the monitors had to be reset by removal of the battery. On several occa-

TABLE IV. Response to Monitors with Different Specific Filters

	Filter	Response (ppm)
Response to 82 ppm Acetylene Alone	Nonspecific[A]	276.9
	Old specific[B]	229.7
	Newer specific[C]	153.8
	Newest specific[D]	66.4
Response to 250 ppm CO Alone	Nonspecific	284.1
	Old specific	234.9
	Newer specific	253.8
	Newest specific	255.6

[A]Does not remove interferences: one filter in this group.
[B]More than one year old: six filters in this group.
[C]2.5 months old: three filters in this group.
[D]One week old: one filter in this group.

sions monitors stopped acquiring data before the end of the measurement period. This happened even though the measurement period was much less than the 12-hour maximum measurement time. This seemed to occur more frequently when the monitors were used in experiments at elevated temperatures.

The sensor leaked in one of the monitors, damaging the copper coating on the inside of the monitor which resulted in erratic zero measurements even though the monitor still appeared to be functioning in other respects.

Conclusions

The CO monitor evaluated provides warning of high concentrations of CO while also measuring TWA worker exposure over the working shift. The monitor had a linear response over the concentration range of 0 to 950 ppm. The short-term response stability was within 3 percent for concentrations greater than 20 ppm for measurement periods of 12 hours. The long-term response stability showed a CV of 9 percent at a concentration of 57 ppm. The monitors responded to 90 percent of final response within 25 seconds for both rise and fall time. The monitor response was not affected measurably by humidity, but increasing temperature resulted in an increasing response to CO. The temperature response appeared to vary from monitor to monitor and at different concentrations. Interferences affected the monitor response in a number of ways. Several reactive gas interferences were removed completely by the CO-specific filters. Other less reactive interferences, such as acetylene, were removed incompletely and variably by the CO-specific filters. Hair spray products provided a large interference when sprayed directly on the monitors and use of these products should be avoided when using the monitors. Exposure to high concentrations of ammonia damaged the sensors in the monitors and reduced their response to CO.

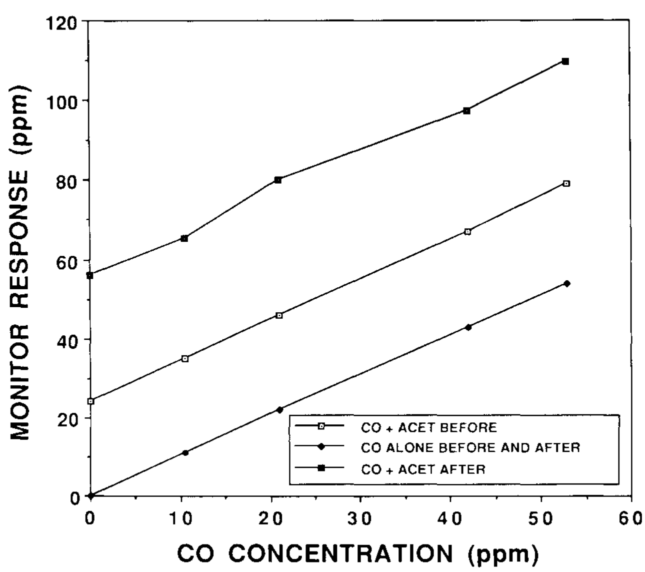

FIGURE 6. Monitor response to CO alone and mixtures of CO and 27 ppm acetylene before and after exposure to 1500 ppm acetylene for 1 hour: CO + ACET BEFORE refers to the response of the monitor to varying concentrations of CO and 27 ppm, acetylene before exposure to 1500 ppm of acetylene for 1 hour; CO ALONE BEFORE AND AFTER refers to the response of the monitor to varying concentrations of CO before and after exposure to 1500 ppm of acetylene for 1 hour; CO + ACET AFTER refers to the response of the monitor to varying concentrations of CO and 27 ppm acetylene after exposure to 1500 ppm of acetylene for 1 hour.

TABLE V. Linear Regression Models of Monitor Response to CO Alone and CO/Acetylene Mixtures Before and After Exposure to 1500 ppm Acetylene

		Linear Regression Models[A]			
		CO Alone[B]		CO and 27 ppm Acetylene[C]	
Monitor	Exposure	Slope (A)	Intercept (B)	Slope (A)	Intercept (B)
A	Before	1.04	0.14	1.00	24.3
A	After	1.04	0.14	1.00	56.0
B	Before	1.05	0.0	1.01	21.7
B	After	1.03	0.7	0.99	51.1
C	Before	1.05	−1.1	0.98	15.4
C	After	1.03	−0.5	0.99	38.3
D	Before	1.03	−0.8	0.99	24.9
D	After	1.03	−0.6	0.97	54.6
E	Before	1.18	−2.2	1.14	19.2
E	After	1.18	−2.2	1.06	43.6
F	Before	1.19	0.8	1.14	28.1
F	After	1.20	0.4	1.15	55.9

[A]Response curves for monitors are in the form AC + B: where C = CO concentration, A is slope of response curve, B is intercept.
[B]CO Alone-Monitor response to 10.5–52.9 ppm CO.
[C]CO and 27 ppm Acetylene-Monitor response to 10.5–52.9 ppm CO and 27 ppm acetylene.

In application the monitor evaluated will be able to provide accurate measurements that are within ±25 percent of the true value, 95 percent of the time for CO concentrations near the PEL as long as they are calibrated at proper intervals. The presence of certain interferences will affect the accuracy of the measurements if the interferences are present at the proper levels.

There are some improvements that would make the monitors more useful under certain conditions. Data could be stored more frequently than once per minute. Because the monitors respond within 20 seconds and CO concentrations can change rapidly, more frequent data storage might give a better picture of the exposure profile. However, if the CO concentration changes more rapidly than the monitor time constant, the monitor may not be able to accurately track the concentration even if more frequent data storage is used. Improved method of removing interferences also might be developed.

Disclaimer

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.

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